Diode Laser Stabilization

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ABSTRACT

Electronic and optical means of stabilizing diode lasers are briefly presented. Experiments with optical locking extended cavity lasers are discussed.

Diode lasers are used in a growing number of applications, such as communications, spectroscopy, metrology and consumer electronics. These lasers have unique attributes that often compel their use in system designs: small size, excellent power efficiency, and the ability to be modulated at high rates. Power outputs in the 10's of milliwatts in the near IR with single spectral and spatial modes are available at reasonable cost. Spectral linewidths of 10 to several hundred MHz are typical. For time scales on the order of minutes, nominal stabilities of frequency (~ 0.1 ppm) and of output power (~0.1%) result from simple temperature stabilization and constant current drive sources.[1-3] However for many applications these residual fluctuations may be detrimental. Longer term drifts and aging effects may also pose problems. For some interferometric and high resolution spectroscopy applications the low coherence is a limitation. In these cases linewidth reduction, frequency stabilization and output power stabilization can be achieved by the appropriate use of feedback, either electronic[4,5] or optical[6-8] or both.

Center frequency drift may be reduced by stabilizing the laser to an optical cavity with a relatively uncomplicated low bandwidth feedback loop acting on the injection current. A frequency discriminator may be realized by a number of established locking techniques[9] such as side-locking, frequency modulation followed by phase sensitive detection, or a polarization type lock.[10] Frequency modulation by means of the injection current also modulates the power according to the slope efficiency of the diode (~ 0.2 to 1 mW/mA for AlGaAs lasers). This additional AM will cause an intensity dependant frequency offset in the control loop. This can be compensated by monitoring the laser power along with the cavity transmission in a balanced detector configuration. Confocal cavities or ring cavities are useful as a frequency reference since the alignment can be such that no direct reflection is returned towards the laser. However the degenerate mode structure of confocal cavities makes it difficult to use them for high precision frequency references. Non-confocal two mirror cavities exhibit symmetrical unperturbed resonances, but necessitate the use of optical isolators; even a very small reflection (~ -80 dB) returning to the laser mode will influence the laser frequency in a manner that depends upon the phase of the returning wave.[11] Optical cavities can be good short term frequency references due to their mechanical stability and the high signal-to-noise that is available. For averaging times longer than ~1 s an atomic or molecular reference line will generally provide better frequency stability. Table I lists some transitions that have been used as frequency references for

Table I. Published studies emphasizing frequency locking diode lasers to atomic and molecular spectral lines

wavelength	reference	
671 nm	Li	12
766	K	13
780,795	Rb	14,15,16,17,18
801	Ar	19
810-842	Ar	20
819	H_2O	21
826	U	22
852	Cs	23,24,25,26
1.25-1.54 um	Ar, Kr	27
1.3	HF	28
1.51	NH_3	29
1.524	Kr	30
1.536	C_2H_2	31

locking diode lasers from visible wavelengths out to 1.5 um. See also the earlier table of ref 18. The stability required will drive the choice of locking schemes. Frequency control on the order of the discriminator width Δv divided by the signal-to-noise is possible, but each spectral line must be individually evaluated for possible systematics such as pressure or field sensitivities.[17,21] Opto-galvanic detection[32] is an approach that is particularly convenient due to the large number of noble gas absorption lines throughout the near IR and the availability of small gas filled lamps. However for high precision references, field induced level shifts and broadening in the discharge are concerns not encountered in passive cells. Iodine,[33] tellurium[34] and uranium[35] have also been extensively studied for wavelength calibration and atlases of transitions have been compiled. In addition, accurate frequency measurements of certain infrared transitions of OCS, N_2O and other molecules have been published.[36] We note here in passing that although a closed loop discriminator error signal is often useful to diagnose control loop problems, extreme care should be exercised when using it to draw conclusions of stability or linewidth. Heterodyne measurements between independently stabilized lasers will offer more convincing evidence of stability. Since the spectral linewidth of diode lasers is determined by the magnitude of the frequency noise out to 10's of MHz, a relatively slow feedback loop that adequately locks the center frequency will have no significant effect upon the linewidth. This is in contrast to the case of a typical flowing jet dye laser, where the linewidth is dominated by frequency fluctuations at less than 1 MHz. Extending the bandwidth of current feedback to a diode laser (to 10's of MHz) has been shown to be effective for linewidth reduction.[4,5] Servo considerations include the laser's complex frequency response which depends on the laser's physical construction,[37] and the frequency response of the Fabry-Perot discriminator.[38]

Resonant optical feedback from a confocal (see figure 1) or ring cavity can also reduce the high frequency noise, resulting in linewidths in the 10 kHz range.[6-8] For a certain value of the round trip optical path distance from the laser to the cavity the coupled system's oscillation frequency will be at the peak of a cavity resonance. As the phase of the reflection returning from the cavity drifts from this value due to thermal path length changes, the laser's frequency will be pulled away from the cavity peak, the power reflected back to the laser will decrease and the linewidth will increase from the minimum on resonance. The optimum phase may be determined by dithering the cavity-diode distance and detecting the transmitted or reflected light from the cavity. Irrespective of the phase, the natural (unlocked) laser frequency must be within some range (typically several hundred MHz) of the cavity resonance. If the frequency is initially outside this range, the laser will not lock to the cavity for any value of the phase. Once optically locked, if the cavity resonance drifts out of the lock-range the laser will abruptly break lock and return to oscillation

at its natural frequency. This lock-range increases linearly with the feedback power up to a point marked by the onset of induced mode hopping and further instabilities.[39] The relation of the cavity resonance to the laser's unlocked natural frequency can be controlled to force operation in the center of the lock
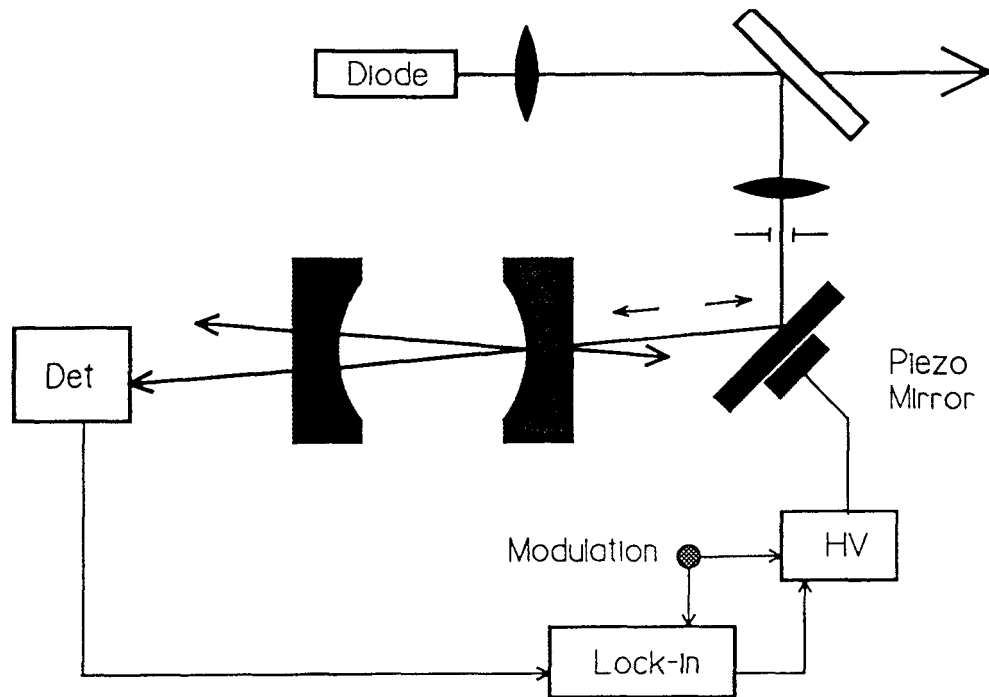

Figure 1   A fraction ($\leq 4\%$) of the diode power is mode matched to a confocal cavity in a V-type alignment. In this geometry only laser light resonant with the cavity is returned to the laser.

range.[40,41] However with phase control alone the system can remain locked for periods on the order of hours with low drift lasers and cavities. The low frequency ($\leq$ several hundred MHz) FM response to modulation of the injection current is suppressed with respect to the free running laser, except at distinct frequencies related to the cavity's free spectral range.[42] The high-frequency, low-modulation-index response of the optically locked laser is essentially the same as the unlocked laser.

With either an electronic or an optical lock to a cavity, the laser's wavelength is restricted to those regions that can be reached by temperature and current tuning of the solitary diode alone. This is a severe limitation for some applications since mode jumps often reduce the actual low noise single-mode wavelength coverage to only about 30% of a given spectral region. This can be increased to 100% coverage by the use of an extended cavity with a frequency selective component such as a diffraction grating. An extended cavity diode laser has the additional advantage that the linewidth is reduced from the case of the diode alone. This situation is very attractive for spectroscopic, optical pumping and laser cooling applications. Two regions of stable operation exist, strong and weak feedback in relation to the laser facet reflection. These coalesce into a single region for very short cavity lengths.[43] Using high diffraction efficiency gratings[44] and both

anti-reflection coated and uncoated lasers, the majority of extended cavities built in our laboratories have been designed for operation with strong feedback.

Inherent fast (Lorentzian) linewidths of about 10 kHz are realized from extended cavity diode lasers
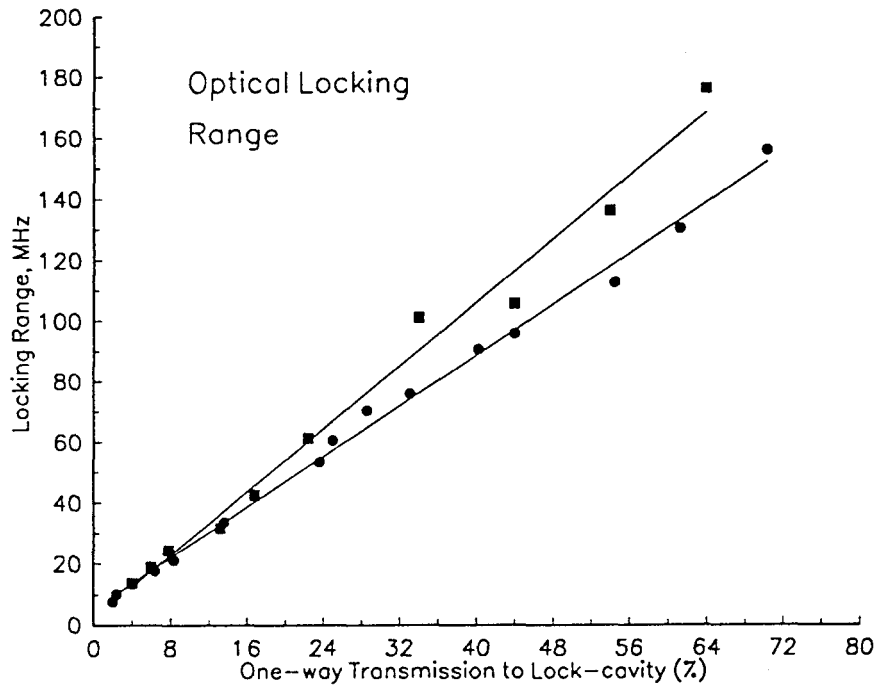

Figure 2   Typical lock-ranges measured for optically locking an extended cavity laser to a confocal cavity with a 300 MHz free spectral range, and a finesse of 75. The two sets of data are for slightly different alignments of the laser to the lock cavity.

with cavity lengths of ~10 cm. This corresponds to a flat (white) spectral density of frequency fluctuations S_ϕ of approximately 3×10^3 Hz^2/Hz. However, the actual FM noise spectrum increases at roughly a $1/f$ rate below 100 kHz due to mechanical and thermal fluctuations. These low frequency contributions to the frequency noise serve to increase the free-running extended cavity linewidth for observation times longer than about 10^{-5} s. Thus when the laser's spectrum is measured by a scanning FP cavity or a narrow atomic resonance, the linewidth will typically appear to be several hundred kHz. This low frequency FM noise contribution is amenable to correction via low frequency electronic feedback to a piezo-mounted mirror in the laser cavity.[45] A "folded" design utilizing a small lightweight mirror to direct the beam towards the grating permits the mirror's mechanical resonance to be sufficiently high so as to not be a problem. This combination of grating feedback and low bandwidth electronic feedback to the cavity length results in a tunable, narrow linewidth source that can be conveniently locked on a spectral line at any wavelength within the gain bandwidth of the diode (approximately ± 10 nm at a fixed temperature). This range may be shifted ~0.25 nm/K by temperature tuning the diode.

Further reduction of the fast linewidth may be possible with additional optical feedback from a confocal cavity to the extended cavity laser. Preliminary results with ~5 cm long extended cavity lasers and 4 MHz linewidth confocal resonators show linewidth reductions by factors of about 3, when measured with a separate high finesse cavity. These extended cavity lasers are not as well coupled to the outside world as the diode alone (80% diffraction efficiency as opposed to the usual 30% facet reflection). This and the
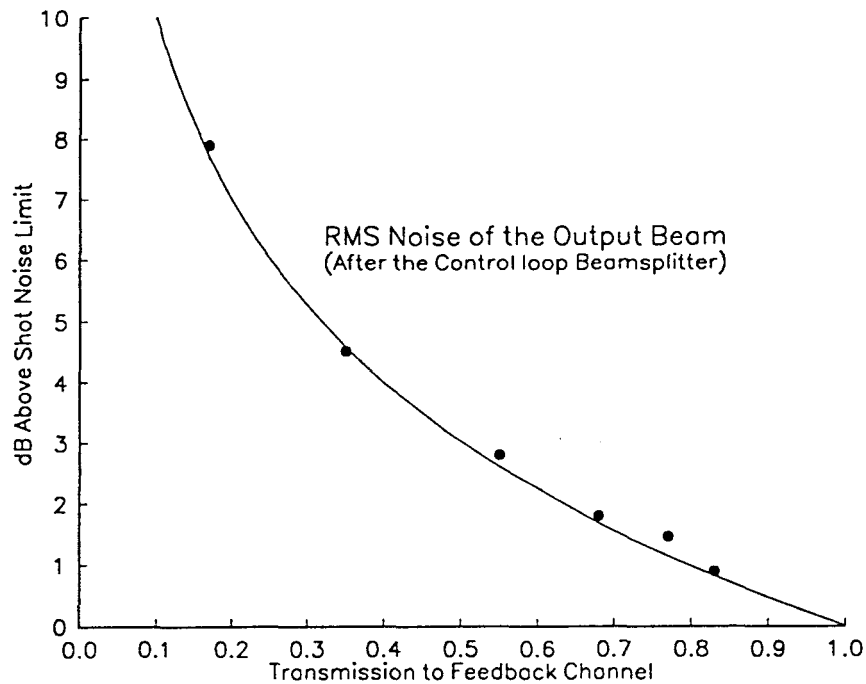

Figure 3. Intensity noise (dB above the shot noise level) vs. the fraction of the laser output power used for the control loop. Noise reduction to 3 dB above the shot noise limit is possible using a 50/50 beamsplitter.

extended cavity length results in a much higher Q oscillator than the solitary diode. Consequently locking ranges (see figure 2) of a few hundred MHz were achieved only by using a substantially larger amount of the output power for the lock cavity than in the case of the solitary laser.

Compared to some other types of tunable laser sources, a single-mode diode laser can exhibit relatively low intensity noise. This is strongly dependent upon the operating conditions and the Fourier frequency of interest. With injection currents well above threshold and in a stable single-mode regime (with low mode partition noise[46]), the detected rms photocurrent fluctuations for frequencies above several kHz are generally 5 to 10 times higher than the shot noise level. This technical noise can be reduced by sampling a portion of the laser beam and applying negative electrical feedback to the injection current. A natural question is how much of the laser output beam is required by the control loop to reduce the residual intensity noise. We have measured the intensity noise reduction of a 780 nm laser operated in an extended cavity configuration. We find (see figure 3) that within the feedback bandwidth, the fluctuations can be reduced

to within 3 dB of the shot noise level by detecting 50% of the laser power in the control channel. The excess technical noise with the control loop closed depends (as expected from shot noise considerations) on the fraction of beam power used for the control loop.

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